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Measurement of Atmospheric Attenuation Low over the Sea Surface at 94 GHz

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Methods and equipment were designed to measure atmospheric attenuation low over the sea surface at W Band (94 GHz). Measurements were carried out at the NRL's Chesapeake Bay Detachment, and the results were compared with theoretical values. The method described will provide accurate ships' RCS measurements at W Band, taking into account variations of atmospheric attenuation.

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BACKGROUND

Atmospheric attenuation may strongly influence results of ships' radar cross section (RCS) measurements. At present, the generally used value of atmospheric attenuation at 94 GHz low over the sea is 0.5 dB/km one way. However, depending on atmospheric conditions, this value may vary between 0.3 dB and 1.5 dB/km, due to the absolute amount of humidity in the air. If a ship's RCS is measured at a range of, for example, 7 km, and the atmospheric attenuation is 1.5 dB/km, then the difference between the "real" RCS and the one measured (assuming the standard value of 0.5 dB/km) will be

$$2*7(1.5 - 0.5) = 14 \text{ dB}.$$

This means that the measured RCS will be 14 dB lower than the real RCS.

There are theoretically derived data to obtain the atmospheric attenuation as a function of relative humidity and temperature [1]. In a first approximation, an improvement of accuracy may be obtained by measuring temperature and humidity somewhere close to the radar path and obtaining the atmospheric attenuation from the theoretical data. However, temperature and humidity may vary in the radar path. Therefore, a better method to assess the atmospheric attenuation in the radar path is by direct measurement while the ship's RCS is measured. This report describes the measuring method, the measuring equipment needed, and the results of measurements of atmospheric attenuation low over the sea surface.

BASIC CONSIDERATIONS OF MEASUREMENT

It is not a trivial matter to measure the atmospheric attenuation at W Band low over the sea surface. Effects of multipath need to be eliminated from the results, and the path loss needs to be measured accurately. For example, at a 7-km range, the free-space path loss is about 150 dB one way; the atmospheric attenuation, assuming 0.5 dB/km, will be 3.5 dB. This means that the measurement of the path loss needs to be made with an accuracy of 1 dB or better. For that reason, a method was devised to prevent the transmit power of the source, its antenna gain, the antenna gain of the receiver, or the gain characteristic of the receiver from influencing the results. The only parameters that influence the result are the setting of a calibrated RF attenuator in the antenna line of the receiver, the ratio of the range at which the measurement is made, and the range at which the receiver was calibrated.

Description of the Receiver

The receiver, nicknamed "Livorno receiver" (LR), is a superheterodyne (Fig. 1) with 160 MHz IF, equipped with automatic frequency control and a pulse height threshold. The IF amplifier is logarithmic; its video output is fed to a sample and hold (S&H) circuit. The sample pulse is derived by a pulse height threshold detector circuit. The output of the S&H is fed to a digital voltmeter and a PC-based data-acquisition system. Figures 2 to 6 show the circuit diagrams of the receiver for future reference and service.

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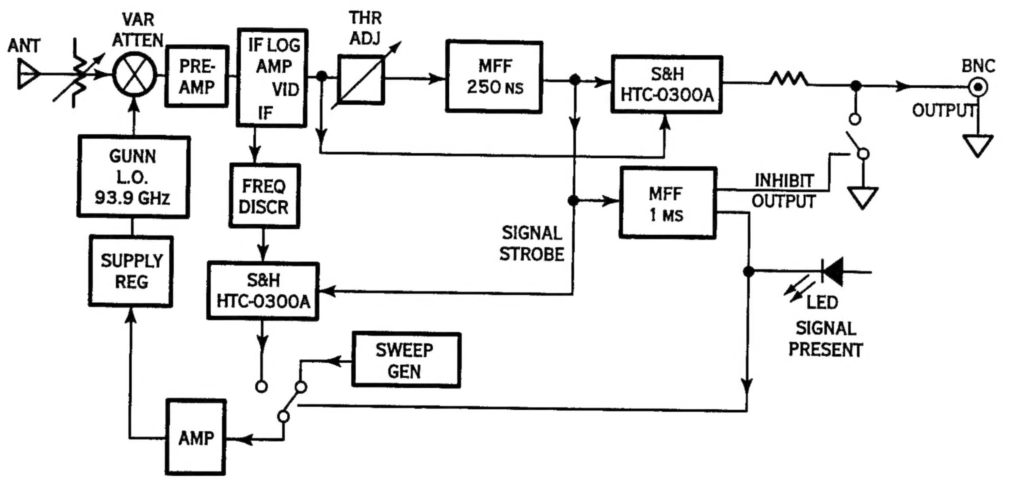

Fig. 1 – Block diagram of the Livorno receiver

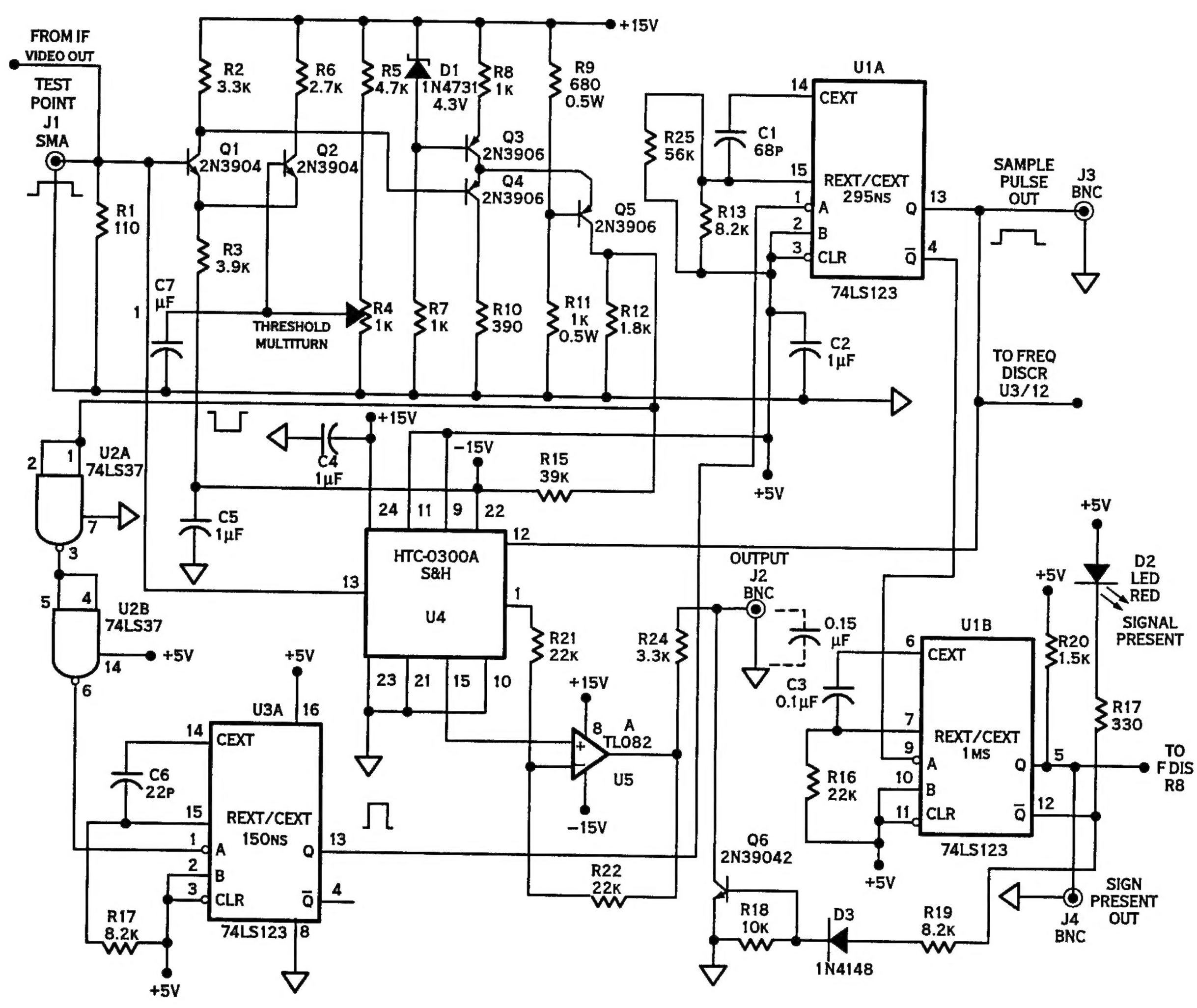

Fig. 2 – Peak detector/sampler

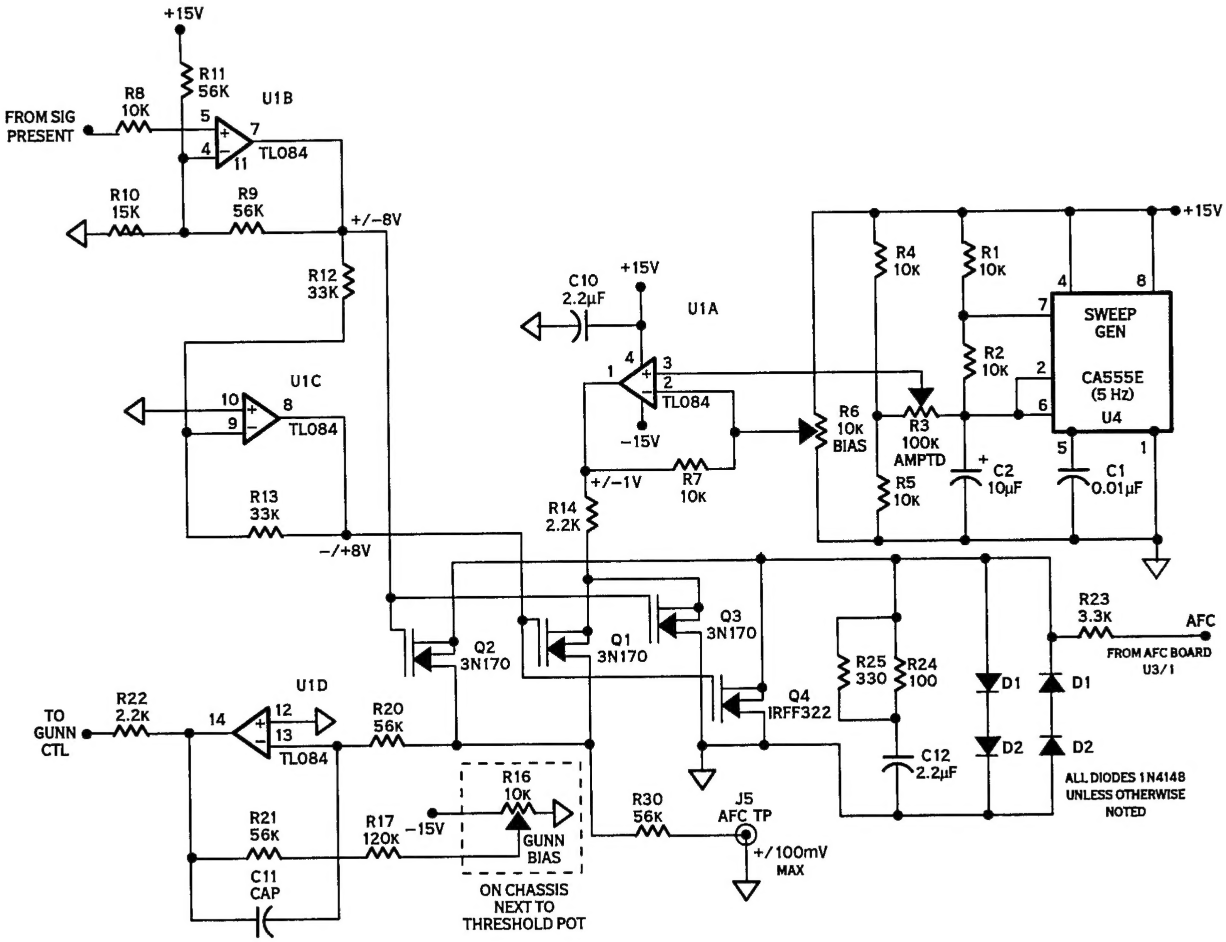

Fig. 3 – Sweep generator and switch

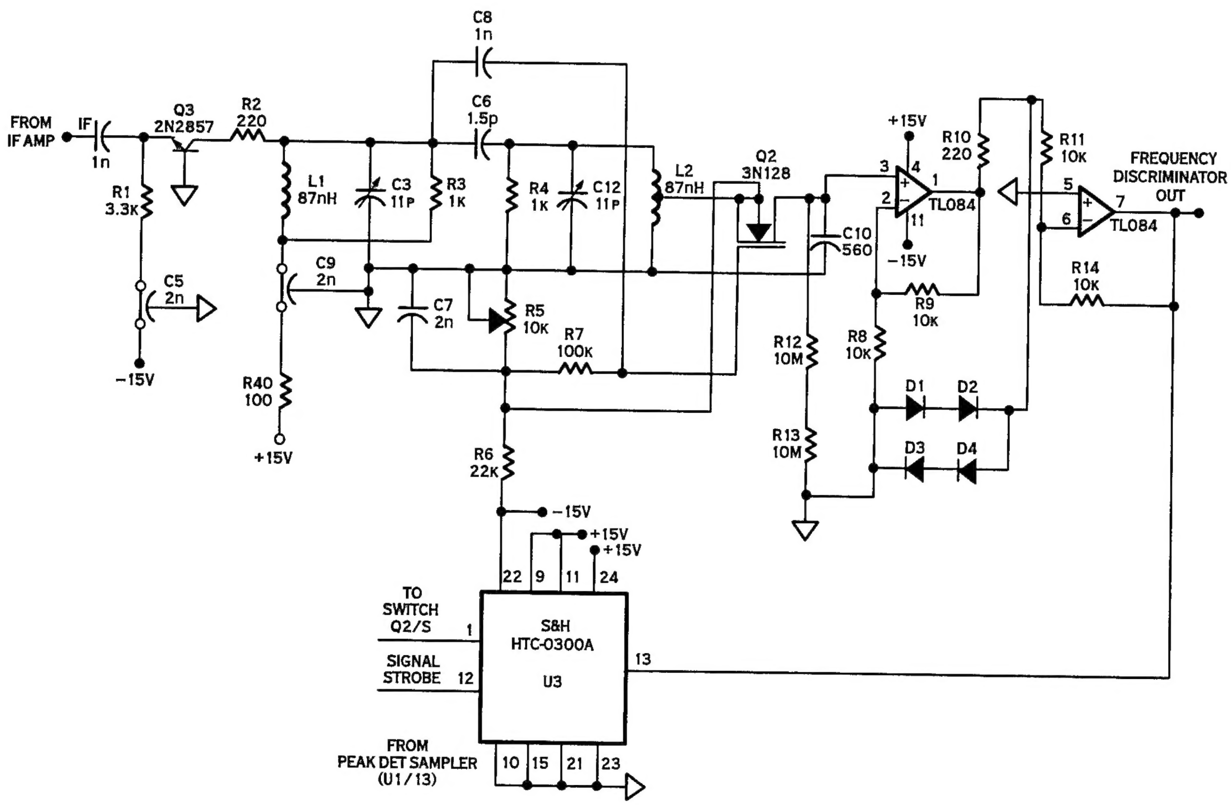

Fig. 4 – Frequency discriminator

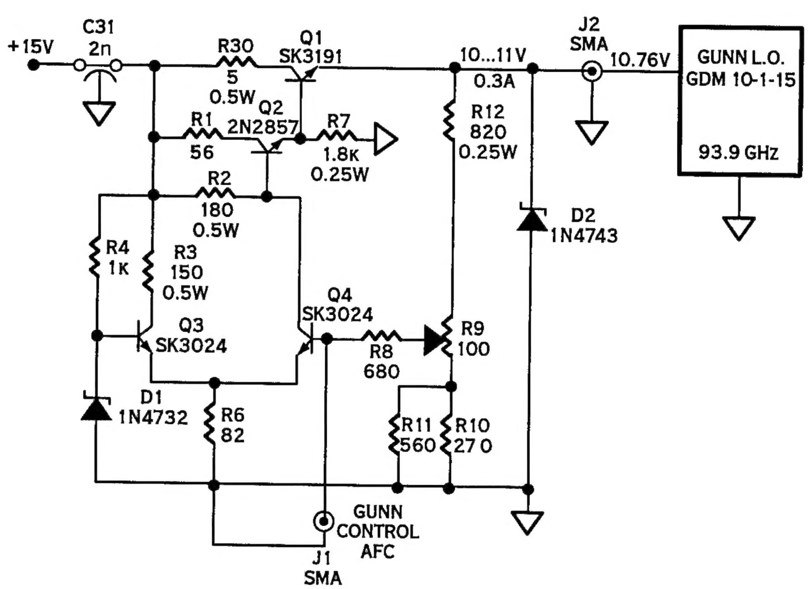

Fig. 5 – GUNN local-oscillator regulator

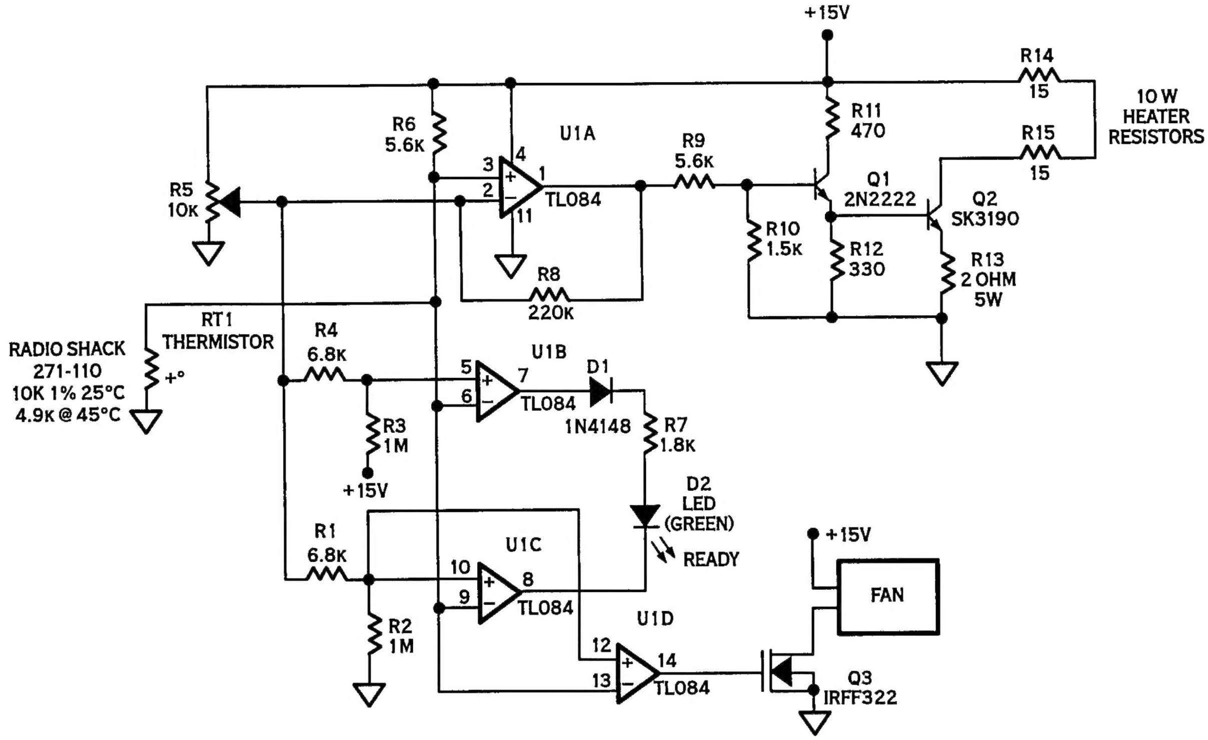

Fig. 6 – Local-oscillator thermostat

Description of the Measurement

The "MIKE" radar was used as a source (Fig. 7). This is a four-quadrant monopulse-tracking radar, transmitting 1 kW pulses at 94.06 GHz (see Table 1). This radar was installed at the shoreline of the Chesapeake Bay, on the seawall of NRL's Chesapeake Bay Detachment (CBD), (Fig. 8). The height of the radar antenna above the water surface was 2.5 m. The measuring receiver, LR, (Fig. 9) was installed on the landing craft LCM8, which then took positions on the bay at various ranges from the radar.

At a particular range, the LR was moved up and down a mast by 2.5 m at a vertical speed of travel of 0.2 m/s to measure the multipath profile. At a given range, a profile of the output voltage was measured as the receiver traveled up and down the mast, thereby providing data on the maximum and minimum signal voltage received. These data were later used to derive the atmospheric path loss, as will be explained subsequently. The range information was provided by the MIKE radar's digital range gate.

The antenna of the LR is an open waveguide. This provided a wide-angle beamwidth both in azimuth and elevation, which made alignment of the antenna toward the MIKE radar not critical. The alignment was achieved manually using a rifle sight that was co-boresited with the antenna.

In addition, a corner reflector of 70-cm edge length was installed on the LCM8, which was reliably tracked by the MIKE radar. This way, the narrow beam (0.7°) of the radar accurately and reliably stayed on the LR.

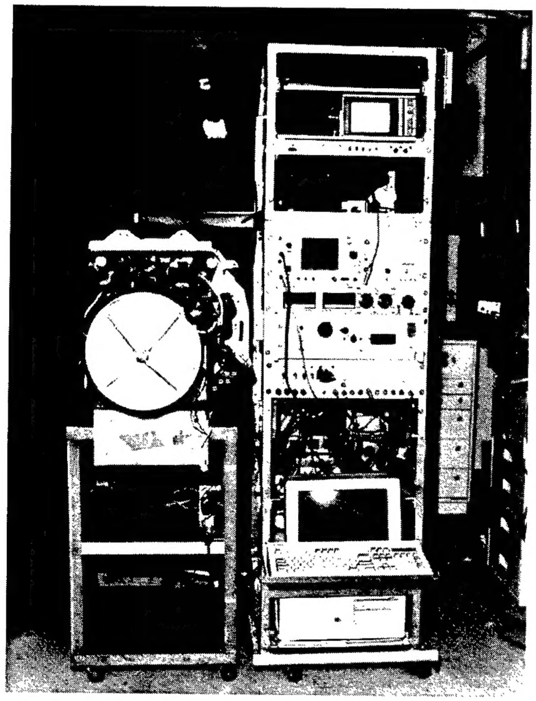

Fig. 7 – MIKE radar

Table 1 — Specifications of MIKE Radar

Radar mode	Incoherent four-quadrant monopulse tracking
Frequency	94.06 GHz
Transmit power	1 kW pulse
Repetition rate	2.7 kHz
Pulse width	500 ns
Antenna beamwidth	0.7°
Antenna gain	42 dB
Polarization	Vertical-vertical
Equivalent radiated power	16 MW

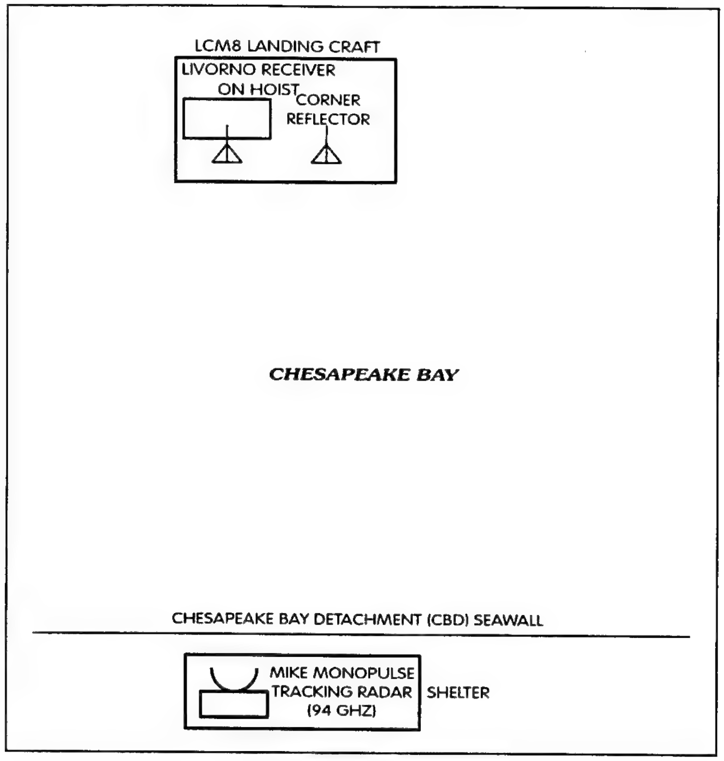

Fig. 8 – Test setup

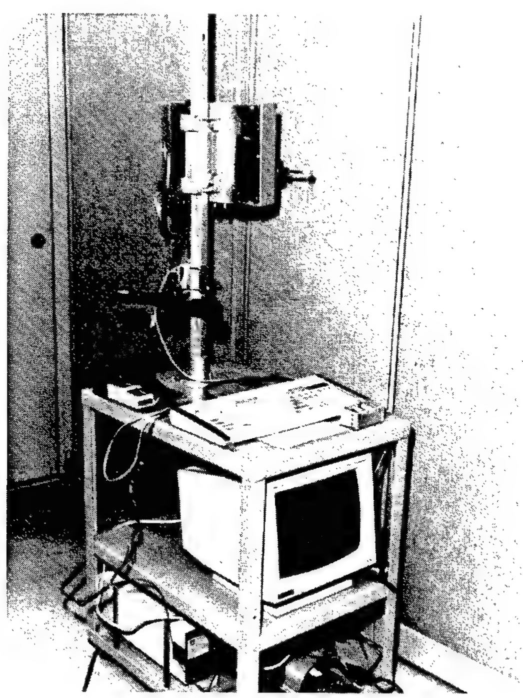

Fig. 9 – Livorno receiver

CALIBRATION

For calibration, the receiver was placed on a pier 145 m from the MIKE radar (Fig. 10). At this range, the receiver is in the far field of the MIKE antenna. Due to the geometry of the setup and the narrow beam of the MIKE antenna, reflections from the water surface did not cause errors in the calibration. In order to keep this narrow beam of the MIKE radar accurately directed toward the LR, a delay repeater [2] was placed close to the LR antenna. The MIKE then tracked the repeater. This repeater provides a delay of 22 μs because MIKE's minimum range is 800 m. The diameter of the radar beam at this distance is 1.8 m. Therefore, the repeater and LR antennas were spaced to within < 0.5 m of each other.

The calibrated RF attenuator in the antenna line of the LR was set to attenuations from 0 to 50 dB, in increments of 5 dB. The receiver output voltage was measured using a digital voltmeter and a PC-based data acquisition system.

As can be shown theoretically, the atmospheric attenuation may be neglected in this calibration, if the calibration range is small in comparison to the range at which the atmospheric attenuation measurement is performed.

ELIMINATION OF SPECULAR MULTIPATH EFFECTS

For sea state 1 and below at 94 GHz, there is considerable specular multipath reflection from the sea surface. For a reflection coefficient of 1, the received power in a one-way signal path may vary between 6 dB above and 20 to 30 dB below that of free space. This influence is eliminated from the measured result as follows.

As the LR travels up and down the mast at a given range, the receiver output is recorded, providing maximum and minimum multipath signals. Figure 11 shows a calculated response of one-way multipath with a reflection coefficient of 1, transmitter height 2.5 m, range 3650 m with the receiver height on the abscissa and the relative receiver output level on the ordinate. For reflection coefficients smaller than 1, the peak is lower than 6 dB, and the minima are more shallow. The voltage at the output of the receiver v_m is shown as:

$$v_m = v_0 (1 + \rho^2 + 2\rho \cos (4\pi XH/(\lambda R)). \tag{1}$$

Here, v_0 is the output voltage of the receiver without multipath, ρ is the reflection coefficient, H the height of the source, X the height of the receiver, λ the electrical wavelength, and R the range. In particular, the maximum of v_m, $v_{m\max}$ is:

$$v_{m\max} = v_0 (1 + \rho^2 + 2\,|\rho|), \tag{2}$$

$$v_0/v_{m\max} = 1/(1 + \rho^2 + 2\,|\rho|). \tag{2a}$$

This means that, in order to obtain the free-space amplitude, the maximum of the multipath signal must be reduced by the factor $1 + \rho^2 + 2\,|\rho|$. The voltage output of the receiver $v_{m\max}$ is measured, and the absolute value of the reflection coefficient can be obtained:

$$v_{m\max}/v_{m\min} = (1 + \rho^2 + 2\,|\rho|) / (1 + \rho^2 - 2\,|\rho|). \tag{3}$$

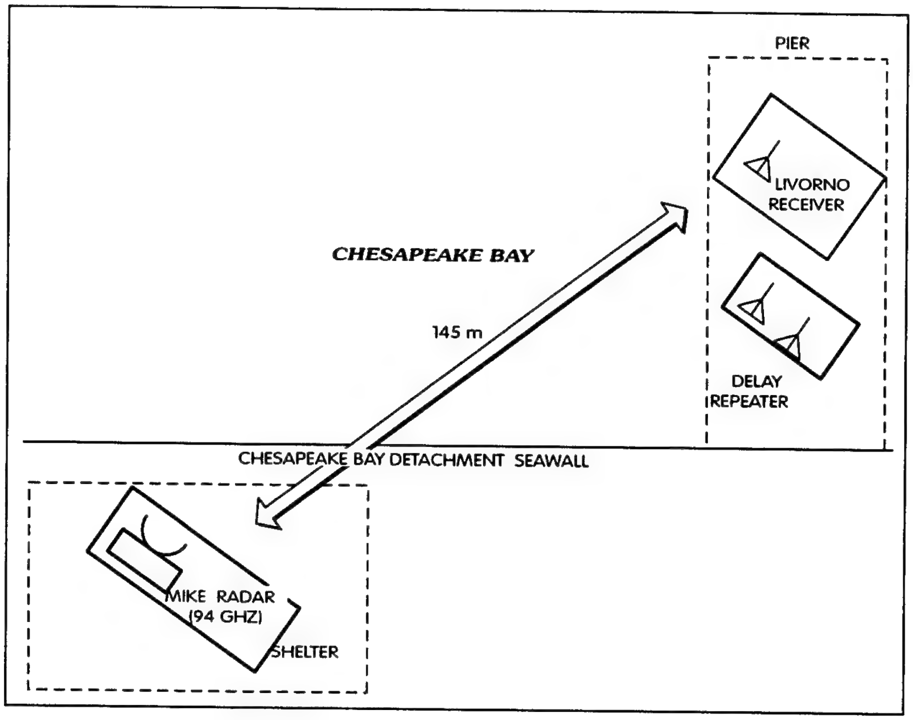

Fig. 10 – Setup for calibration

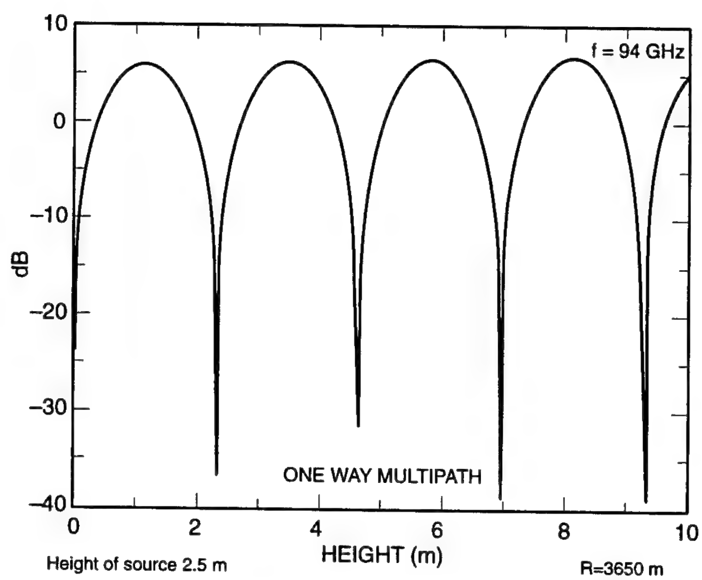

Fig. 11 – Calculated one-way multipath

The ratio v_{mmax}/v_{mmin} was measured. Therefore, $|\rho|$ can be calculated using Eq. (3) and used in Eq. (2a) to obtain the reduction factor v_0/v_{mmax}. Figure 12 shows calculated values of the absolute value of the reflection coefficient vs $p_{max}/p_{min} = v^2_{mmax}/v^2_{mmin}$ using Eq. (3), and Fig. 13 shows calculated values of the reduction factor v_0/v_{mmax} vs p_{max}/p_{min}, using Eqs. (2a) and (3).

RESULTS OF MEASUREMENTS

On August 20, 1996, the LR was calibrated on the pier at a range of 145 m from the radar (as described above), and measurements of the receiver output voltage were made for RF attenuator settings from 0 to 50 dB in steps of 5 dB (Fig. 14). Then the LR was installed on the LCM8, and measurements were made at ranges of 3.65 km and 5.93 km. The wind was calm, and there was little wave action. Therefore, the specular multipath response was quite pronounced. Figure 15 shows the multipath signal vs time as the LR moved up the mast at a speed of 0.2 m/s at a range of 3650 m. The maximum voltage was 1.57 V and the minimum, about 1 V. According to the calibration data (Fig. 14), the ratio of maximum to minimum is 20 dB. With this, Fig. 13 yields a multipath reduction factor of 5.2 dB.

In the measurement at the 3.65-km range, the RF attenuator had been set to 0. From the calibration, it is known that, in order to obtain the same output voltage of 1.57 V that was obtained during the measurement peak, the attenuator would have had to be set to 25.7 dB at the pier. Therefore, 25.7 dB represents the additional path loss caused by increasing the range from 145 m to 3650 m. However, without multipath, the signal received would have been 5.2 dB lower than the multipath peak, resulting in a lower output voltage of the receiver. Lower output voltage, according to the calibration curve (Fig. 14), means higher attenuator set at the pier. Hence, 5.2 dB must be added to the 25.7 dB, resulting in a free space plus atmospheric path loss of 31 dB. Had there been no atmospheric loss, the path loss, by going from 145-m range to 3650-m range, would have increased by 20*log(3650/145) = 28 dB. The differences of 31 dB and 28 dB are the atmospheric loss. Therefore, the atmospheric loss was measured to be

$$\alpha = 3\ \text{dB}/3.7\ \text{km} = 0.8\ \text{dB/km}.$$

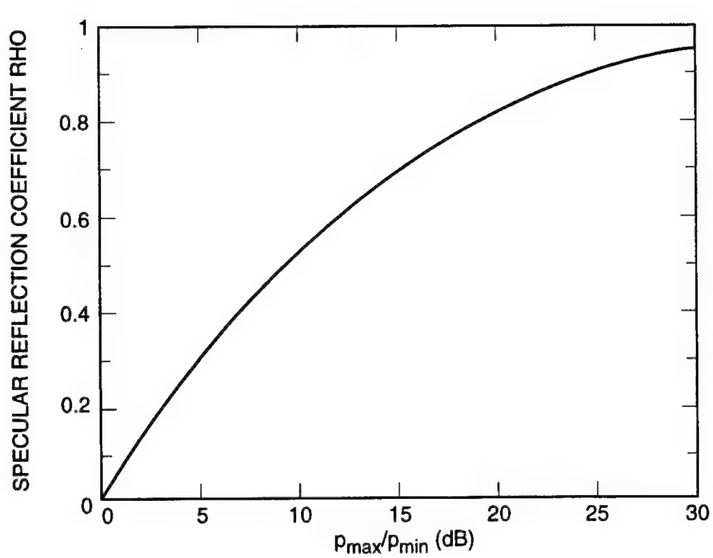

Fig. 12 – Specular reflection coefficient vs p_{max}/p_{min}

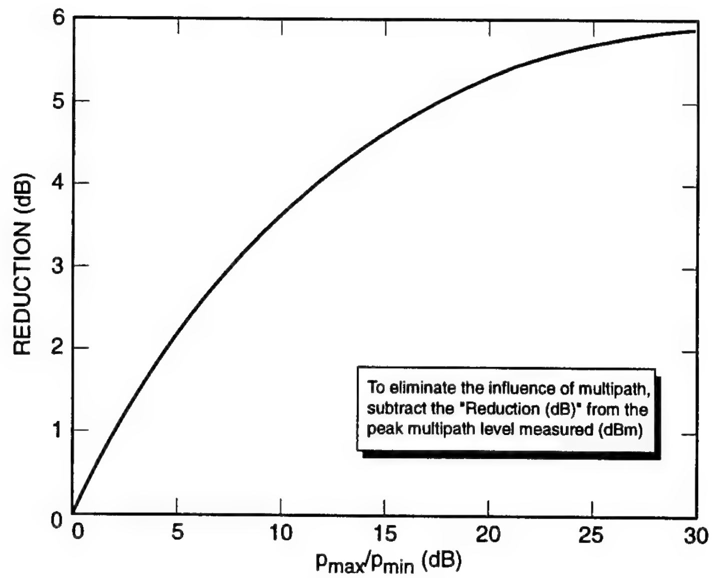

Fig. 13 – Reduction from multipath peak vs p_{max}/p_{min}

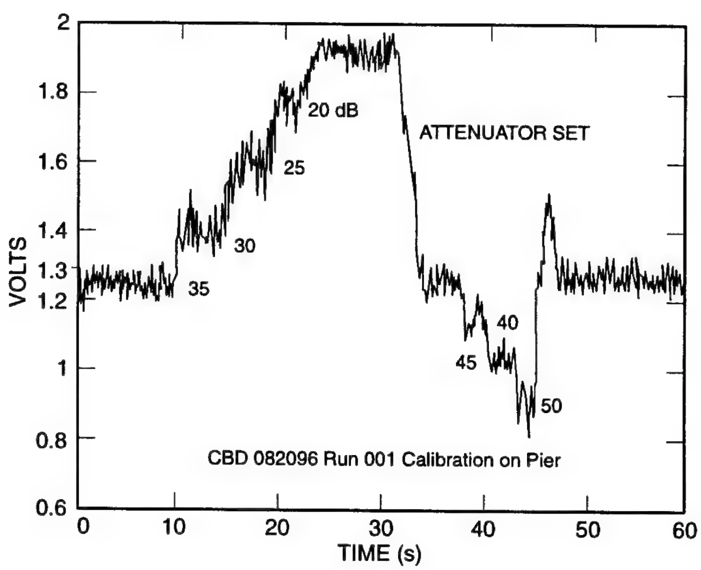

Fig. 14 – Calibration of Livorno receiver

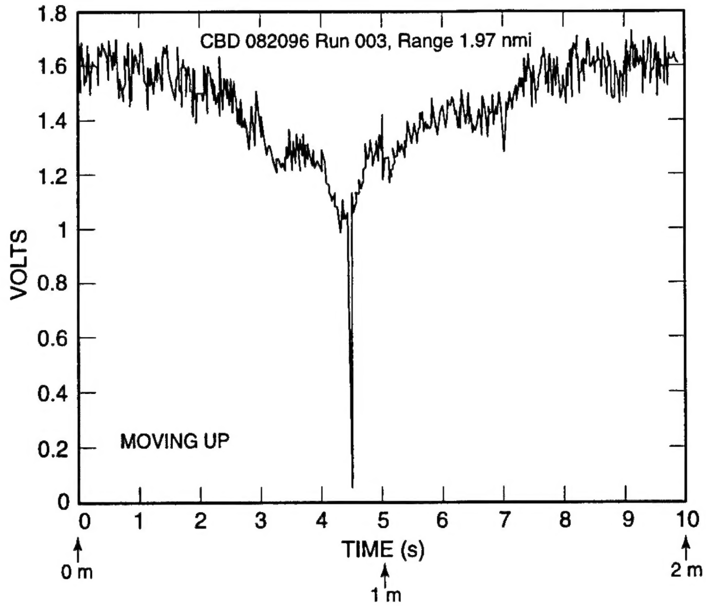

Fig. 15 – Measured multipath response

At the time of this measurement, temperature and relative humidity were measured aboard the LCM8 on deck, in the shade. The temperature was 32° C, and the relative humidity was 50%. Figure 16 shows theoretical curves of atmospheric attenuation vs relative humidity, with temperature as the parameter (adapted from Ref. 1). For these values of temperature and humidity, the curves predict

$$\alpha = 0.87,$$

which is in good agreement. A second measurement at that range yielded 0.9 dB/km and a predicted value of 0.85 dB/km.

Measurements at a range of 5.93 km yielded $\alpha = 0.6$ dB/km with prediction of 0.72 dB/km according to temperature and relative humidity measured onboard the LCM8.

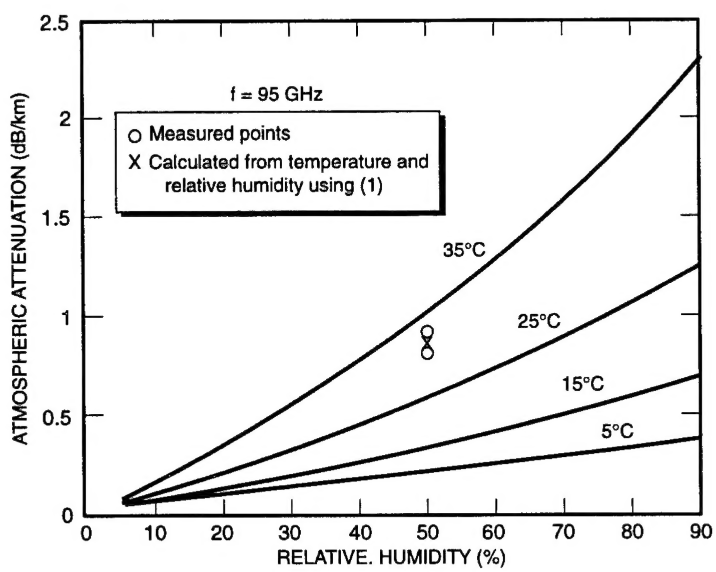

Fig. 16 – Theoretical atmospheric attenuation vs relative humidity, with temperature as parameter

CONCLUSIONS

These data suggest that the atmospheric attenuation at 94 GHz can be assessed reasonably well by measuring temperature and relative humidity onboard of the ship whose RCS is being measured and then using the values given by the theoretical curves. However, more data are required to verify these results.

Measuring the atmospheric attenuation in situ and real time certainly will provide more reliable results. Further, as a "fringe benefit," the absolute value of the reflection coefficient is obtained in this measurement also. This may be of interest because theory predicts that the average cross section of a ship at 94 GHz may vary by 8 dB depending on the sea state. For smooth seas (sea states 0 and 1), assuming that the scatterers on the ship are mostly diffuse, an increase of the average cross section of 8 dB is expected over that seen at rougher seas (sea states 2 and above). The reason is that the multipath peaks vs height are much broader than the minima, so there are more scatterers are in the peaks than there are in the minima. The result is an increase in the average RCS. Therefore, in ships' RCS measurements, the specular reflection coefficient of the sea during the measurement may also be of interest.

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Appendix

CALCULATION OF INCREASE OF RCS AVERAGES DUE TO MULTIPATH CONDITIONS AT 94 GHZ

The results of this calculation are meant to give a basic insight into the influence of multipath reflections from the sea surface on the ships' RCS at 94 GHz. To arrive at the results, the following simplifying assumptions are made:

(a) There are no multiple reflectors like corner reflectors onboard.
(b) There are many reflectors, approximately the same size, distributed equally over the height and cross section of the ship.

At the radar receiver, the powers of the returns from the many reflectors must be added rather than the voltages in amplitude and phase because the phases are randomly distributed due to variations in range. In other words, the returns from various positions in radial direction are uncorrelated. However there is a difference as to the dependence of the returns as a function of the height of the reflectors on the ship. For instance, at certain heights, reflectors will be in the maximum of the multipath return; at other heights, they may be in the minimum or somewhere in between. In a typical scenario (for example, for a sea-skimmer missile approaching at a range of 5 km at 10 m above the sea surface), maxima and minima returns are spaced in height by 0.4 m on the ship. Therefore, for a ship of 10-m height, there will be many maxima and minima over the height such that we are justified in averaging. This will be done by integration, as follows.

It can be shown that the normalized power received by a radar from a point target under multipath conditions is

$$p = (\cos(b) + 2\rho\cos(c) + \rho^2\cos(a))^2 + (\sin(b) + 2\rho\sin(c) + \rho^2\sin(a))^2, \tag{A1}$$

where
$a = 2\pi(X+H)^2/(\lambda R)$ $\quad b = 2\pi(X-H)^2/(\lambda R)$
$c = 2\pi(X^2+H^2)/(\lambda R)$
ρ = specular reflection coefficient
X = height of reflector above the sea surface
H = height of the radar above the sea surface
R = range
λ = electrical wave length
p = power received by the radar from a point target.

Power p is normalized such that for free space conditions, i.e., $\rho = 0$, $p = 1$, as can readily be seen in Eq. (A1).

As can be shown, Eq. (A1) can be written:

$$p = 1 + 4\rho^2 + \rho^4 + 4(\rho+\rho^3)\cos(u) + 2\rho^2\cos(2u), \tag{A2}$$

where $u = 4\pi HX/(\lambda R)$.

The periodic part of Eq. (A2), which, when integrated over one period, comes out to be zero. Therefore, the average of p, p_{av} is the following:

$$p_{av} = 1 + 4\rho^2 + \rho^4. \tag{A3}$$

For reflection coefficient $\rho = -1$ $p_{av} = 6$ or 7.8 dB.

This means that under the assumptions outlined above for sea state 1 or below (specular reflection at 94 GHz), the average RCS of a ship may be about 8 dB higher than that seen at sea states above 1 (no specular reflection at 94 GHz). The physical reason for that is the fact that since the maxima of the multipath response are broader than the minima, more reflectors will be located in the maxima than in the minima, thereby causing an overall increase of the average of up to 8 dB.